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Eutrophication assessment of Lake Manzala, Egypt using geographical information systems (GIS) techniques

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ABSTRACT

Lake Manzala is in grave danger of suffering pollution from the drainage of industries, agriculture and urban sewage that affects the physio-chemical and biological parameters in the lake. A geographical information system (GIS)-based method of lake trophic status assessment was undertaken to study the spatial distribution of eutrophic conditions of Lake Manzala. In the present study, tabular data supported by field checks have been analyzed by GIS functions and operations to assess, monitor and model the environmental conditions of the lake. A representation of the spatial distribution was developed using the inverse distance weighted (IDW) interpolation method. The eutrophic state index was calculated to describe the state of the lake's environment. A GIS overlay technique was applied to synthesize the information into a final map illustrating the spatial distribution of eutrophication conditions within the study area. The different levels associated with trophic status classification using GIS were then discussed in relation to environmental change and external loading from tributary inflows. The study revealed that the lake changed to eutrophic freshwater. This change is due to the increase of freshwater inputs and nutrient loading associated with agricultural land reclamation and urban waste disposal.

Key words | GIS, ILWIS, lake eutrophication, Lake Manzala, nutrient loading, TSI

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INTRODUCTION

There are two universal systems of lake classification. These are the physical or thermal classification and the classification by trophic level (Chapman 1992). For Lake Manzala, as eutrophication is the principal water quality problem, the classification was based upon the trophic level. The concept of trophic status as a system of classification was introduced by early limnologists such as Naumann (1919) and Vollenweider (1968), and has been subject to continuous development up to the present time (Pouriot & Meybeck 1995). The process of eutrophication underlying this scheme is one of the most significant processes affecting lake management and is therefore described in more detail. Eutrophication is the process by which lakes are enriched with nutrients, increasing the production of rooted aquatic plants and algae to levels that are considered to be an interference with desirable water uses such as recreation, fish maintenance and water supply. Eutrophication can also result in detrimental effects on the biological stability of lake and reservoir ecosystems, affecting virtually all the biological populations and their interactions in the water body. Consequently, eutrophication of lakes and reservoirs can have significant negative ecological, health, social and economic impacts on human use of a primary and finite resource.

It is also well known that the growth and proliferation of aquatic plants is a result of the utilization and assimilation of organic materials through photosynthesis. Thus the plant biomass increases by the uptake of available phosphorus and nitrogen from the water. It was found that the nutrient that will control the maximum amount of plant biomass is the nutrient that "runs off" or reaches a minimum before other nutrients. Therefore, under certain condition, nitrogen may reach a minimum value before phosphorus and, as a result,

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control the maximum amount of plant biomass and vice versa. This situation depends on the relative amounts of nitrogen and phosphorus required by aquatic plants and their availability in the water body. Accordingly, a mass ratio of available forms of nitrogen and phosphorus (N/P) was used to calculate the limiting nutrient in water. In this respect different ratios were suggested by many authors (Chiaudini & Vighi 1974; Forsberg & Ryding 1980; Smith & Shapiro 1980). The most conservative ratio suggests that when the N/P ratrio is between 5 and 10, either nutrient could be limiting and if less than 5, nitrogen is the limiting nutrient for plant growth. The N/P ratio in a water body can also be useful as a diagnostic tool for assessing the types of algae existing under different nutrient conditions (Smith 1983), relating nutrient ratios to the concept of resource competition as a major factor affecting phytoplankton community structure. He reported that low total N:total P ratios appear to favor green algal dominance in natural lakes in the temperate zone.

The multidimensional nature of the eutrophication phenomenon means that no single variable is representative of the eutrophication status of a given water body. Therefore, more trophic criteria or indices using multivariate approaches have been proposed. Carlson (1977) offers the most suitable and acceptable method for evaluating lake eutrophication (e.g. a trophic state index (TSI)). Lake eutrophication assessment requires not only a large number of variables, but also a spatial distribution of eutrophication levels based on each of the variables. The spatial assessment of eutrophication levels may become quite complicated, since the function and dynamics of each parameter may, however, lead to different eutrophication tends. There seems to exist, then, a need for appropriate methodologies and tools capable of synthesizing spatially the eutrophication trends presented by various parameters. By synthesizing such trends, a final thematic map illustrating the spatial distribution of eutrophication conditions can be created. Fortunately, this can be easily performed through the use of a geographic information system (GIS).

Geographic Information Systems (GIS) are a powerful tool that is being used to analyze satellite images, aerial photographs and hardcopy maps to derive information and create solutions for a specific problem by using definite criteria. The GIS system is very powerful for the analysis and creation of models that incorporate the relations between the different features on the surface and their effect on the environment. GIS can be used to perform a number of fundamental spatial analysis operations. Its major advantage is that it allows the user to identify the spatial relationships between various map features. More precisely, overlay techniques allow us to synthesize different map layers, based on a database where the information is stored as a whole. Comparisons, as well as further analyses, among and between both variables and layers can be easily performed (GIS 1994).

But why is it important to assess lake water quality? This question can best be answered by looking at Lake Manzala as a natural resource and at its socio-economic aspects. Lake Manzala is the largest of the northern Nile Delta coastal lakes. It is an important and valuable natural resource area for fish catch, wildlife, hydrologic and biologic regimes and table salt production. It produces about 50% of the fish catch of the northern lakes and fresh water fisheries. Lake Manzala, the area under study, is characterized by special sensitive environments. Human activities including discharge of sewage and industrial waste and the impact of canal and road networks have a serious impact on the water quality of the lake. The lake has been gradually transformed from a largely marine or estuarine environment to a eutrophic freshwater system.

Previous studies on the hydro-chemical characteristics of Lake Manzala have been carried out by many authors. Montasir (1937) described in detail the overall ecology of lake Manzala. El-Wakeel & Wahby (1970) studied in detail the water chemistry of the lake. Wahby *et al.* (1972) studied the preliminary changes of the hydrographic and chemical conditions of the lake during 1967 after the construction of the Aswan High Dam and Faraskour's Barrage. Bishara, (1973) studied the biology of the Tilapia species in the lake as well as the dissolved oxygen and chlorisity of lake water. Yousef (1973) studied fish production and the biology of the mugillidae family and some chemical parameters, average chlorisity and dissolved phosphate, which were 3.918 g/l and 0.543 μM/l, respectively. Bishai and Youssef (1977) studied some chemical characteristics of the lake and observed that variations of chlorosity, inorganic phosphate and reactive silicate were highly significant and there was a clear relation between the progressive dilution by the drainage waters and the concentration of nutrient salts in the lake water. Halim & Guerguess (1978) studied some environmental parameters of the lake water. Shaheen & Youssef (1978) studied some chemical parameters and the fish production of Lake Manzalah. MacLaren Engineers (1982) presented the most comprehensive assessment of the lake and admit in their results that nutrients from the major drains have created eutrophic conditions in those parts of the lake closest to the drain outlets. These conditions have changed the aquatic biota, leading to a less diverse but highly productive system, which supports a high yield of Tilapia fishery, especially in the El Genki area. The lake is still an important habitat for many species, including a number of aquatic birds. Dowidar & Abdel-Moati (1983) studied the distribution of nutrients in the lake. Dowidar & Hamza (1983) studied the phytoplankton production of the lake. El-ghobashi (1990) studied the Biological Studies on the Western Region of Lake Manzala.

All the previous studies admit that the major problem of the lake is the increase in nutrients loading into the lake especially from the input drains that accelerate the eutrophication process occurring within the lake. But almost no research tries to quantify and qualify the eutrophication processes occurring in the lake. This research objective is to integrate GIS techniques into the lake eutrophication assessment process and then to study the resulting spatial distributions of lake eutrophication conditions by using the trophic state index and N/P ratio concepts.

STUDY AREA DESCRIPTION

Lake Manzalah, the largest natural lake in Egypt, is located between 31°00″–31°30″ N and 31°45″–32°22″ E longitude. It extends 64.5 km in its maximum length and 49 km in its maximum width and 239 km in total length of the shore line. The lake is bordered by Mediterranean Sea to the north and the north-east, the Suez Canal to the east, Dakahlia and Sharkia Provinces to the south and the Damietta branch of the Nile to the west. There are narrow outlets at El-Bighdadi, El-Gamil and El-Qaboti on the northern side of the lake. The lake is connected with the Damietta branch of the Nile through the El Inaniya Canal. Therefore, the southwestern corner of the lake receives the majority of its fresh-water input from the Sirw and Fariskur pumping stations, and the Inaniya Canal. The lake is shallow, with an average depth of about 1.25 m (Dowidar & Abdel-Moati 1983). The water level of the lake is often subjected to variations, which may expose or cover extensive areas along its shore. The lake bottom is covered with sandy-silt and silty-clay with an accumulation of cardium shells. Lake Manzala is productive in fish, 90% Tilapia spp. Carbs. Shrimps are also fished from this lake.

Lake Manzala is a highly dynamic aquatic system that has undergone considerable physical, chemical and biological changes during the past century. This was as a result of different aspects of human impacts, such as the closing and/or opening of straits, establishment of the Aswan High Dam, silting of the lake, continuous drying processes for cultivation purpose and human settlement and pollution with different kinds of water discharge into the lake. Six main agricultural drains used to flow into Lake Manzala and affect its water quality. Drainage water contributes about 98% of the total annual inflow to Lake Manzala. There are seven drains carrying fresh and drainage water to the lake. The following are these drains with their relative contribution of the total flow in water, as shown in Figure 1:

- *Hadous Drain*. This is the largest drain in the eastern delta, serving some 1756.96 km^2 of agricultural land. It contributes about 49% of the total inflow.
- *Bahr El Baqar Drain*. This serves an agricultural area of about 119.2 km^2, and also receives about 300 million m^3/yr of sewage from Cairo. It contributes about 25% of the total inflow
- *Sirw Drain*. This serves 152.8 km^2 and contributes about 13% of the total inflow
- *Ramsis Drain*. This is about 24 km long and discharges a relatively small amount of water to Lake Manzala. It contributes about 4% of the total inflow.
- *Fariskur Drain*. This serves about 44.48 km^2 and contributes about 4% of the total inflow.
- *Matariya Drain*. This serves 111.2 km^2 of land under agricultural reclamation. It contributes about 2% of the total inflow.

MATERIALS AND METHODS

Data collection

Measurement and sampling of the lake's water for analytical purposes was performed monthly on a regular basis, from

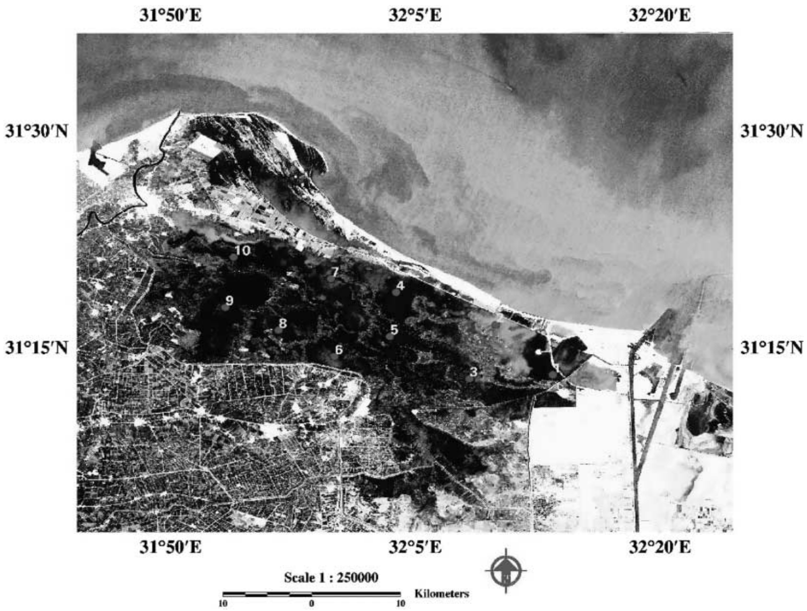

Figure 1 | Geographical location and distribution of sampling sites.

July until December 2003 within the MELMARINA project monitoring part. The water samples were collected from 10 stations covering the main area of the lake. The geographic positions of these locations were determined using GPS, as illustrated in Figure 1. The measurements of the required parameters (transparency, chlorophyll-a, total nitrogen, total phosphorus, nitrate and phosphate) were obtained following the procedures described by APHA (1995). Accordingly their levels were corrected as a quality control check. Water samples were collected from 20 cm below the water surface to avoid floating material, using a high quality PVC Nisken's bottle.

Transparency was measured using a white enameled Secchi disk. Chlorophyll-a determination was performed in the other exact volume of the 500 ml water sample which was filtered on the same day of collection using GF/C filters. The filters were kept in a deep freezer until analysis. Chlorophyll-a in the phytoplankton cells retained on the filters was extracted by using 90% acetone and measured spectrophotometrically at 630, 645, 665 and 750 nm wavelengths (Strickland & Parsons 1972). Total phosphorus and total nitrogen were estimated in unfiltered water samples according to Valderrama (1981). Synthetic standards as well as international reference materials (batch VKI 9-2-0894 for NO_3–N and PO_4–P and batch 10-2-0894 for TP and TN) were intended for quality control, i.e. they were typically intended for measurement and control of the trueness and precision of analysis, as well as for the implementation and optimization of analytical instruments and methods. There is no morphometry and vertical profile measurements as the impact of internal loading processes were not addressed in this study.

Trophic State Index (TSI)

In the present study, the Carlson trophic state index (TSI) was used to provide a single quantitative index for the purpose of classifying and ranking lakes, most often from the standpoint of assessing the trophic state of the lake. In recent years the Carlson index appears to have attained general acceptance in the limnological community as a reasonable approach to this problem. This is a measure of the trophic status of a body of water using several measures of water quality including transparency or turbidity (using Secchi disk depth (SD) recordings), chlorophyll-a (CHLA) concentrations (algal biomass) and total phosphorus (TP) levels (usually the nutrient in shortest supply for algal growth).

TSI ranges along a scale from 0–100 that is based upon relationships between Secchi depth and surface water concentrations of algal chlorophyll, and total phosphorus. Its major assumptions are that suspended particulate material in the water controls Secchi depth and that algal biomass is the major source of particulates; values below 40 are generally considered to represent oligotrophic conditions and values above 60 representing eutrophic conditions. The values between 40–50 represent mesotrophic conditions, the values between 50–60 represent moderately eutrophic conditions and values above 70 represent hypereutrophic conditions.

A set of equations were then derived to describe these relationships with higher values corresponding to increased fertility, that is, more eutrophic. An increase in TSI of 10 units corresponds to a halving of Secchi depth and a doubling of phosphorus concentration:

$$\mathrm{TSI\,(TP)} = 10(6 - \ln(48/\mathrm{TP})/\ln 2) \quad (\mathrm{TP\ in\ \mu g/L}) \tag{1}$$

$$\mathrm{TSI\,(CHLA)} = 10(6 - (2.04 - 0.68\ \ln(\mathrm{CHLA}))/\ln\ 2) \quad (\mathrm{CHLA\ in\ \mu g/L}) \tag{2}$$

$$\mathrm{TSI\,(SD)} = 60 - 14.41\,\ln(\mathrm{SD})\,(\mathrm{SD\ in\ m}). \tag{3}$$

There has been a tendency to average the three variables rather than to prioritize their use (Kratzer & Brezonik 1981; Osgood 1983). Perhaps this is just a natural tendency for humans to seek the central tendency, or it might reflect the concept that the trophic state is defined by a number of variables:

$$\mathrm{Average\ \ TSI} = \frac{[\mathrm{TSI(TP)} + \mathrm{TSI(CHLA)} + \mathrm{TSI(SD)}]}{3}. \tag{4}$$

Nitrogen to phosphorus (N/P) ratio

As the principal nutrients entering Lake Manzala are phosphorus and nitrogen, a balance of these is necessary for the development of the undesirable growths associated with eutrophication. Therefore, the N/P ratio has been calculated from the lake data for nitrogen as total nitrogen and phosphorus as total phosphorus and represented using GIS as a limiting factor responsible for controlling eutrophication (McPherson *et al.* 1982).

Calculation of eutrophication levels and generation of thematic maps

The data were represented by the Software Integrated Land and Water Information Systems (ILWIS) developed and marketed by the International Institute for Aerospace Survey and Earth Sciences (ITC 1998). It is a geographic information system (GIS) with image processing capabilities. The ILWIS software allows you to input, manage, analyze and output geographical data. From the data you can generate information on spatial and temporal patterns on the Earth's surface.

ILWIS in this research is used as a tool for constructing a GIS for the study area. Also GIS has been used for displaying the TSI(CHLA), TSI(SD) AND TSI(TP) values on a geographically registered map and in colour to correspond with varying levels using the inverse distance interpolation method (IDW). By categorizing the interpolated values, a clear illustration of the different trophic levels was developed on three thematic maps. Finally, it is used for the calculation of the overall trophic state index and the N/P ratio by using the overlaying technique to illustrate the spatial distribution of eutrophication conditions within the study area.

To estimate unknown values, we use weighted linear combinations where the weights account for the distance to the nearby samples by using the inverse distance method. This method relies on the idea that data are more likely to be useful if they are measured near the point of interpolation. Thus more weight is given to the closest samples and less to those which are furthest away. The value of an intermediate point is thus calculated from the summation of the product of the observation values v_i and weights, divided by the summation of weights. The inverse distance algorithm used is by making the weights inversely proportional to any power of the distance:

$$v_1 = \frac{\sum_{i=1}^{p} \frac{1}{d_i^n} v_i}{\sum_{i=1}^{p} \frac{1}{d_i^n}}$$

where v are the sample values and d are the distances from the p samples.

As we reduce n, the weights given to the samples become more similar. For progressively larger values of n

the closest sample would receive a progressively larger percentage of the total weight, as shown in Figure 2.

The (IDW) interpolation method has been widely used on many types of data because of its simplicity in principle, speed in calculation, ease of programming and credibility in interpolating surfaces (Lam 1983).

The overlay of the thematic maps

The overlaying of the maps was implemented using the map calculation procedure of the ILWIS. It is used for the execution of most spatial analysis functions and modelling operations. It integrates spatial and tabular data.

The overlay technique, widely used in GIS applications, was applied to synthesize the three thematic maps and develop the final eutrophication map. The following steps describe the procedure used to generate the final thematic map as shown in Figure 3:

- development of TSI for each indicator scale from 0–100,
- analysis of the three thematic maps on a cell by cell basis,
- overlaying the three maps to generate the final eutrophic state map,
- classifying the final map using the Carlson classification scheme of lakes.

RESULTS AND DISCUSSIONS

The thematic maps TSI(CHLA), TSI(SD) and TSI(TP), developed using the (IDW) interpolation method were calculated and presented spatially in Figures 4, 5 and 6.

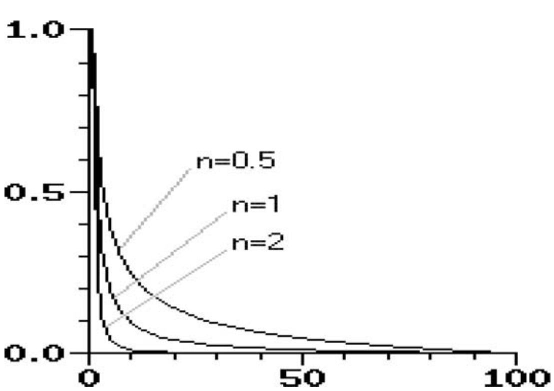

Figure 2 | The weight at different *n* values for different distances.

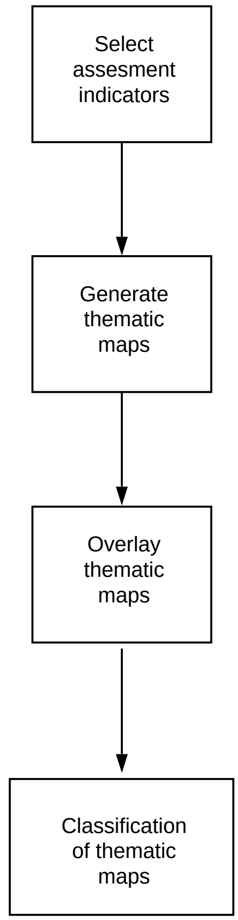

Figure 3 | Diagram for the GIS-based method for lake eutrophication assessment.

The final TSI map developed as a result of the overlay technique is given in Figure 7.

Figure 4 shows the spatial distribution of TSI(CHLA). From it, the middle part of the lake is characterized mainly as hypereutrophic, while the eutrophic field is distributed in the eastern part of the lake. The eutrophication levels near the discharge of drains are representative of eutrophic to extremely hypereutrophic conditions. Figure 5 illustrates the spatial distribution of TSI(SD). From it, the middle part of the lake is characterized mainly as severely eutrophic, while the western part of the lake is upper mesotrophic to moderately eutrophic. The eutrophication levels in the eastern part are mesotrophic. Figure 6 illustrates the spatial distribution of TSI(TP). From it, the middle part of the lake is characterized mainly as upper mesotrophic, while the northwestern and the eastern parts are characterized to be

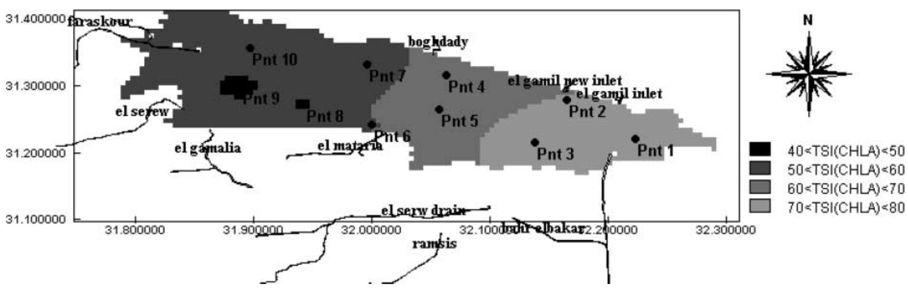

Figure 4 | Spatial distribution of the lake trophic state index based on CHLA.

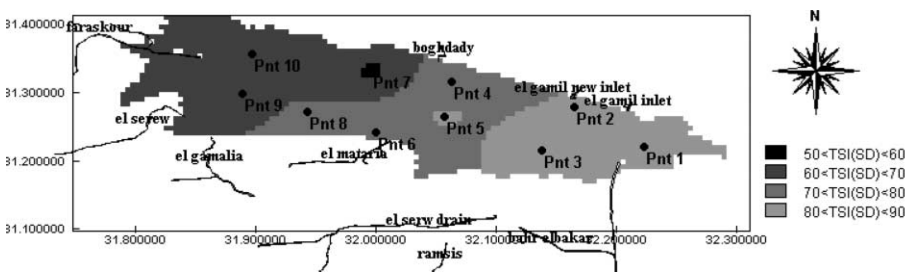

Figure 5 | Spatial distribution of the lake trophic state index based on SD.

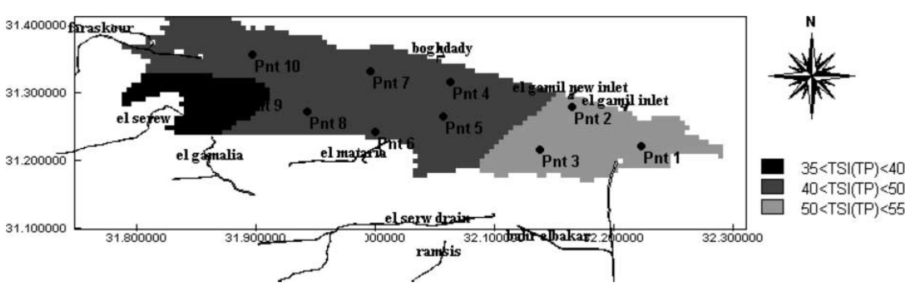

Figure 6 | Spatial distribution of the lake trophic state index based on TP.

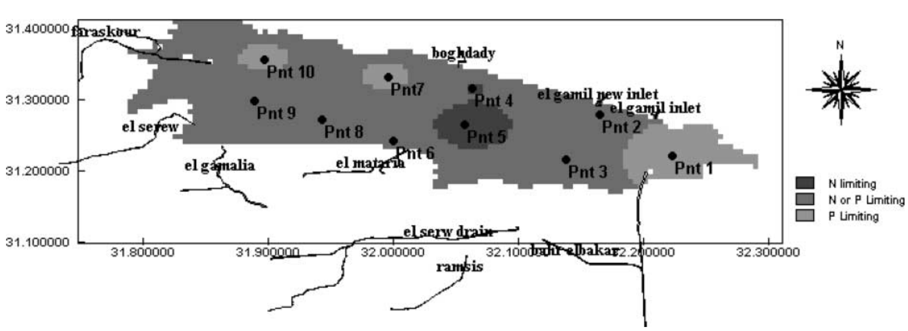

Figure 7 | Spatial distribution of the N/P ratio of Lake Manzala.

moderately mesotrophic. The eutrophication levels in the remaining parts of the lake are mesotrophic.

The N/P ratio was calculated from the data for nitrogen as total nitrogen and phosphorus as total phosphorus collected at ten sites along the lake and presented spatially in Figure 7. From the map, it is shown that the N/P ratio is more than 5 in most parts of the lake, which means that phosphorus controlled the plant biomass. The finding that phosphorus is the limiting nutrient factor in Lake Manzala is in agreement with the concept that a large lake receiving runoff from non-point sources will tend to have a higher N/P ratio (Thomann & Muller 1987). Also this result explains the rise of chlorophyll and Secchi depth indices above the phosphorus index in Figures 4, 5 and 6, which could be due to the algae becoming increasingly phosphorus limited.

Finally, the overall distribution is illustrated in Figure 8. Eutrophic conditions (TSI 60–70) cover most of the study area, especially in the eastern part where it receives the discharge of the Bahr El Baqar drain that accounts for 60% of the nutrient loadings into Lake Manzala (McLaren Engineers, Planners and Scientists Inc. 1984) and also at the western part of the lake which receives the discharge from the Faraskour and Hadous drains that contribute about 30% of the nutrient loading into the lake. The middle part of the lake is characterized as moderately eutrophic. This eutrophic condition may result in nuisance macrophytes, algal scums and low transparency that discourage swimming and boating. A very limited area of the lake is classified as mesotrophic which can cause hypolimnetic anoxia resulting in loss of salmonids. Walleye may predominate. Figure 9 shows the general eutrophication status of the lake.

CONCLUSIONS

Nutrients from the major drains have created eutrophic conditions in those parts of the lake closest to the drains outlets. The water classification of Lake Manzala is based upon the calculation of the trophic state index (TSI) and the N/P ratio. A geographical information system (GIS)-based method is derived for lake eutrophication assessment in order to study the spatial distribution of eutrophication conditions in lake environments by using the IDW interpolation techniques within the ILWIS software.

Results from the study indicate that the boundaries associated with different trophic levels (mesotrophic, moderately eutrophic and eutrophic) could be clearly defined in a final eutrophication map. The northern sector and parts of the western sector, which are relatively unaffected by wastes and nutrient loading, provide a reservoir for "natural" fish and other aquatic species. The nutrients load in the southern sector of the lake exceed the environmental assimilation capacity and tolerance limits of major commercial fish species due to the acceleration of algal growth and decrease of oxygen level (Goel 1997).

Therefore, the integration of TSI calculations into GIS is important in creating a complete picture of the trophic

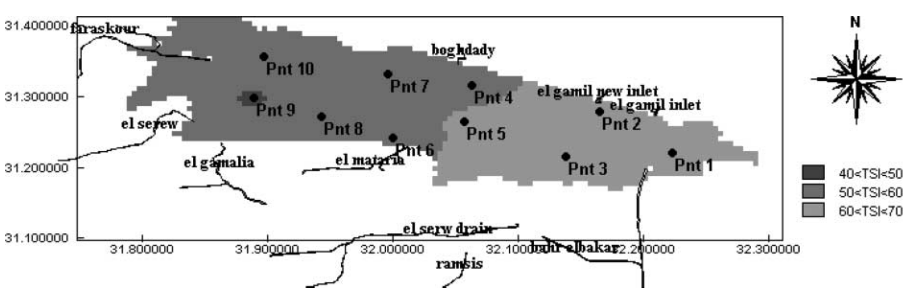

Figure 8 | Spatial distribution of the lake trophic state index.

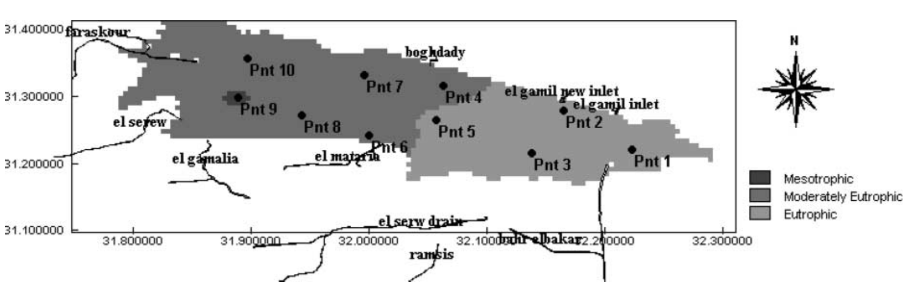

Figure 9 | General trophic state of Lake Manzala.

state of the lake. The GIS manages the spatial and attribute data, in addition to manipulating and displaying the results of TSI calculations. The proposed method will help a lot in making a good water quality management plan of the lake to ensure its sustainability. As an example, the hypereutrophic areas of the lake can be improved with management activities in the contributing drains.

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